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Review

How electricity utility practitioners in the United States approach power system resilience

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ABSTRACT

This study explores the understanding and practice of resilience among electrical utilities in the United States, focusing on how practitioners in the utility sector conceptualize and apply resilience in their work. As electricity becomes increasingly central to modern life, powering critical infrastructure and essential services, the resilience of power systems has gained prominence in energy policy and planning. However, there is a lack of standardized definitions and approaches to resilience in both academia and practice, particularly from an energy service perspective. The research employs a qualitative approach, utilizing semi-structured interviews with experts (practitioners) from transmission and distribution utilities in the United States to examine their definitions, understanding, and applications of resilience. By adopting a grounded theory approach, the study aims to identify key themes and concepts that practitioners associate with power system resilience. The findings outline that there is no clear definition of resilience amongst utility practitioners, and resilience and reliability are often used interchangeably/synonymously as there are no fixed indicators for resilience amongst practitioners. At present, unlike reliability, utilities are not including resilience as a term in their long-term resource planning, and neither are they reporting resilience-based indicators to any of the government agencies. The findings contribute to the ongoing dialogue on energy resilience and offer a foundation for developing more comprehensive and context-specific approaches to building resilient energy systems that prioritize critical services and vulnerable populations.

1. Introduction

Electricity is key to deriving almost every energy service required for modern human comforts and is critical to building resilient communities [1, 2]. Power systems now serve as the lifeline for critical infrastructures such as health, education, defense, communications, and overall national security [3, 4]. Economic and human development indicators often depend on the capability and resiliency of access to energy services [5]. The most evident example is in the case of any climate-induced disaster or during the war, power system protection is considered a priority to derive other forms of services. Further, impacts on the electricity system have cascading effects on multiple aspects of community resiliency [6, 7]. The resiliency of a power system is a proxy indicator for understanding the energy services adaptability of a community to respond, recover, and rebound from a disaster. Historically, energy planning predominantly relied on the trilemma of energy security, affordability, and sustainability, a relatively new application of energy resilience is gaining traction as a key element in energy policymaking [8, 9]. This shift to an increased focus on energy resilience stems from the study of the resilience of centralized oil and gas systems, other energy generation systems, and energy services access [10]. The increased influx of renewable electricity and utilization of electricity as end-use energy, even in the traditionally bereft transportation sector, has led to an increased focus on power system resilience [11]. This focus on power system resilience has primarily focused on system capabilities modeled through various software, with limited consideration for human agency, particularly for electrical utilities [10]. The socio-technical nature of power systems and socio-technical system resiliency is largely under-researched, with a primary focus on developing a technically resilient power system. Electrical utilities are the primary stakeholders that apply, define, and shape the application of energy system resiliency [12].

Given the evolving restructured competitive electricity markets in the USA, which is primarily led by utilities, the practitioners' understanding of power system resiliency is of critical importance [13]. Currently, utility practitioners' understand resilience as reliability, with a limited understanding of resilience in practice within the energy industry. Researchers and power system scholars are continually debating how utility professionals understand and define resiliency at the transmission and distribution levels [14, 15]. Scholars have argued that resilient energy services is an enigma even when it is a prerequisite to understanding the nature of electricity system resilience for the community [16]. Given the importance of understanding the power sector's resilience and how it impacts energy services access, it is imperative to understand how practitioners working in the utility sector understand energy resilience.

The energy resilience of a power system and its capabilities are typically understood and captured using reliability indicators. Power system scholars utilize metrics such as System Average Interruption Duration Index (SAIDI) and System Average Interruption Frequency Index (SAIFI) to understand the average power interruption to consumers and outages in the system [17]. However, these indicators do not tell us which customers are affected in what ways, particularly for the people who are most vulnerable in a particular power system. The current lack of a standard definition for resiliency, particularly energy system/service resiliency, in academia and practice has created a challenge to comprehensively develop and build models that look at community resiliency through an energy service approach. Energy systems resilience must prioritize access to energy services for those who are vulnerable in the case of energy services disruption [18].

This paper aims to explore the understanding and practice of resilience among electrical utilities in the US. As there is currently limited research on how utility practitioners utilize resilience in their work, this paper serves as an initial foray into examining the meaning and utilization of resilience in transmission and distribution utilities. The paper uses a qualitative semi-structured interview approach to interview experts from utilities at the transmission and distribution level to understand and explore the practitioners' current definition of resiliency.

We explore the current themes discussed by the practitioners to apply the concept of resilience coherently. Based on this grounded theory approach, we situate energy resilience into community resiliency through an energy service approach, which is under-represented in the study of energy resilience yet is key in developing a resilient power system.

2. Background: electric utility & resilience in the United States

2.1 Resilience of the current utility sector in the United States

The electric utility in the US has its roots in a decentralized system, with initial regulations starting at municipal, thereafter state, and only later at the federal level [19]. The role of electricity has expanded since the enactment of the Rural Electrification Act in 1935, which led to the US-wide electrification of rural US households through electric cooperatives with the foremost goal of providing electricity services to rural farms [20, 21]. However, the expansion of utilities through the late 1990s till today involves a centralized system with vertical integration of a sector that has been considered a natural monopoly of the Public Utility Commission (PUC) or Public Service Commission (PSC) operating at the state level [22]. Vertical integration involves a single company's ownership of three main parts of the power system: generation, transmission, and distribution [23]. This vertically integrated sector required regulation, as they were deemed natural monopolies. The major focus of scholarship has been on the economic argument for regulating monopolies to provide people with electricity at a reasonable price. However, given the nature of the power system, where electricity cannot easily be stored and maintaining grid frequency is of utmost importance in the power system, system reliability was also a major concern for the regulators [20]. Following the deregulation of the electric power industry, wholesale power markets were formed in parts of the US, with separate entities owning generation, transmission, and distribution. Administration of the wholesale markets in deregulated regions is the responsibility of Independent System Operators (ISOs)/Regional Transmission System Operators (RTOs). ISOs/RTOs are also responsible for maintaining grid reliability and resiliency [19, 24]. Both regions with vertically integrated utilities and restructured markets in North America must adhere to North American Electric Reliability Corporation (NERC) standards to ensure the reliability and security of the bulk power system (Figure 1). Some of these standards encompass various aspects of system operation, including critical infrastructure protection (CIP), which safeguards physical and cyber assets. Utilities must follow transmission operations (TOP) standards, ensuring real-time system monitoring and coordination and transmission planning (TPL), which involves assessing future system needs and reliability. Utilities have to maintain the NERC standards, such as the development of emergency plans (EOP) for system disturbances, modeling, data, and analysis (MOD) to support accurate system simulations, and resource and demand balancing (BAL) to maintain system stability.

The electrical utility sector today is complex, involving multiple layers of actors, institutions, and interests. The US electricity segment contains over 24,645 electricity generation power plants with over 11,000 utility-scale plants with a nameplate capacity of over 1 MW. With the growing utilization of electricity as a means of service, the utilities' transmission and distribution network capacity is expected to grow at a brisk pace, particularly after the implementation of the Inflation Regulation Act (IRA) aimed at infrastructure improvement. The increase in central dependency on the power grid to provide end-use energy makes electrical utilities' understanding and application of resilience even more critical in the restructured electricity market. Restoration and recovery of services are of prime importance. Electricity is seen as a means for people to incur services, and the need for services can range across multiple dimensions of social vulnerability; hence, it is essential to understand the meaning and application of resilience amongst professionals in the transitioning electrical utility sector.

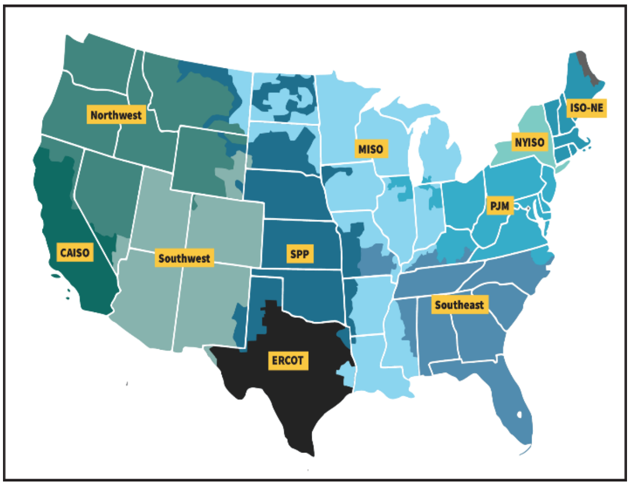

Figure 1. Regional Transmission Organizations (RTOs)/Independent System Operators (ISOs)

2.2 Electricity utility services & resiliency

Electricity is a core commodity required to derive a multitude of services for human needs and comforts. Any attack on the supply or distribution of electricity can disrupt those multitude of human services. The National Academy of Sciences (NAS) has outlined that power systems are increasingly vulnerable to physical and nonphysical attacks, such as cyber-attacks and extreme weather [24]. The current US electric system is increasingly vulnerable to climate-induced disasters, which impacts community resilience as well since it is tied to electricity system resilience [18]. However, unlike other commodities, utilities cannot independently improve resiliency because they are linked to each other through distribution, and supply purchase and sale and work within a market response model since each is competing to gain consumers and remain profitable [24]. Hence, the overall goal of providing resilient energy services and maintaining a resilient grid (both at transmission and distribution levels) sits at a crossroads of myriad economic, climate, and social priorities. Power outages translate into direct service disruptions, which can vary across a spectrum from a minor inconvenience to a fight between life and death for some community members. For instance, in a recent power outage in Michigan, 467,000 people were left without power in freezing cold weather [25]. The same was observed during the Texas power crisis, where 4.5 million people were left without power [18], and those with access to electricity paid very high electricity bills because of the market principles of increased prices with constrained electricity supply and high demand [26, 27]. The impact of power outages is compounded by the fact that utilities are not required by federal law to report power outages. There are no rules to report the resiliency of a power system till a recent ruling by the Federal Energy Regulatory Commission (FERC) that requires interstate electric transmission providers to file one-time informational reports assessing the susceptibility of their systems to extreme weather events to the NERC. However, this rule is only applicable to power outages caused by extreme weather events. The scope of this rule is limited to current and planned policies of transmission providers when exposed to extreme weather events. Apart from this rule, power utilities are mandated to report reliability data to NERC. The NERC then assigns ‘cause codes’ from the reported data that identify the cause of the power outage event. These cause codes cover momentary (less than a minute) and sustained (more than a minute) outages. The cause codes are the basis of our current understanding of the energy resilience of a power system.

The NERC data reporting requirement notwithstanding, scholars have increasingly attempted to develop metrics to gauge power outages and report power system resilience [28]. Technical standards of reliability, such as the System Average Interruption Duration Index (SAIDI)/System Average Interruption Frequency Index (SAIFI), measure the reliability of electricity service. SAIFI and SAIDI are international standards created by the Institute of Electrical Electronics Engineers (IEEE). These indicators are used by transmission and distribution companies across the world to measure, report, and track the reliability of power systems. Each of the participating utility managers in this study submitted data to EIA through Form 861, which is the annual electric power industry report and contains reliability indicators such as SAIDI, SAIFI, and CAIDI. Form EIA 861 collects annual information on the status of electric power industry participants involved in the generation, transmission, and distribution of electric energy. Power outage reporting requirements are in the form of standards set by NERC (Event Reporting Standard EOP-004-4) [29], according to which utilities are to report events that cause outages exceeding a certain threshold of either a loss of a load of more than 300 MegaWatts (MW), and/or impacts over 50,000 customers. However, these metrics are associated with restoring and/or improving the physical infrastructure and exclude the impact on community resilience. There is a lack of academic agreement on defining or measuring resilience in the context of power systems. Often, it is used synonymously with reliability, which is extensively used in power system studies and has agreed-upon indicators and metrics. Reliability has been defined by the Department of Energy as “the ability of the system or its components to withstand instability, uncontrolled events, cascading failures, or unanticipated loss of system components”. On the other hand, resilience encompasses human factors as well, as its scope includes the differential and compounding impact of power outages on communities [30, 31]. To put it simply, a power system can be reliable but not resilient because of limited consideration of the impact of outages on different groups of people over time-based on a range of vulnerabilities caused by energy service disruption. Reliability, when used as a synonym with resilience, only captures limited information of who is getting impacted by the power system design failures and the ways in which utilities are trying to minimize this failure. Through this study, we are trying to bridge this gap by understanding how utility managers understand and define resilience and how they foresee the future of developing a resilient power system that can cater to the energy service needs of all people.

3. Research methodology

This study is an initial foray into understanding energy resilience through conversations with professionals about the use and definition of the energy resilience term in their practical work. Semi-structured interviews are considered an appropriate method for inductive research when the intent is to understand the meanings and how stakeholders use a particular concept, which in our case is energy resilience in the context of energy and disaster policymaking [32-34] have stated that semi-structured interviews are one of the best forms of data collection during the exploratory phase of a study. This qualitative research tool suits our study as our goal is to answer 'how utility managers think, define, and take action on energy resilience'. We do not intend to test any hypothesis about the utility functions. We use the data collected from the interviews to identify new insights and propose further research. This method is criticized for being vulnerable to bias, particularly social desirability bias, and not providing a means to generalize the research result [35]; however, our goal is to provide new conceptual insights that can be explored further in future empirical work. Given the exploratory nature of our study with no intention to prove a particular hypothesis, we make no claim to generalize the research results. Hence, this is an appropriate method and form of analysis. We structured the interview into two modules: Prevention of Transmission & Distribution (T&D) losses and Restoration/Recovery.

3.1 Data collection

Utility experts were selected for the interviews to explore understanding and use of resilience in power systems operations in the US. The potential respondents were selected through an iterative process of snowball sampling [35]. The interviews were conducted between August 2022 and February 2023. We interviewed utility providers with territories in roughly tens of states in the contiguous US and one unincorporated territory of the US. Twelve interviews were conducted with eighteen participants. Out of the twelve interviews, one interview was telephonic; two were in-person interviews; one company submitted written responses to the interview questions, and the other eight were conducted online. The choice of the means to conduct the interview (in-person, over the phone, online) was based on the preference of the interviewee. Out of the eighteen respondents, nine were one-to-one interviews, and the rest were group interviews - one with a team of four people, one with a team of three people, and another with a team of two people. In the United States, electric utilities operate in a highly competitive market and hence are apprehensive of sharing information that might hurt their profitability due to asymmetric information. The initial respondents were recruited through available professional referrals and by contact through information available on utility websites. Over forty emails for interview recruitment were sent to different utilities, including utilities working at the transmission and distribution system levels. The unit of study is electrical utility; hence, utility managers were interviewed depending on the scale of the utility. For small utilities, we had a single participant, while in large transmission system operators, once we had a team of four people, and one was a team of three people.

3.2 Data analysis

Stake [36] and later Sovacool et al. [37] state that qualitative data analysis involves segregating data into themes and understanding those themes and their relation to each other. Miles and Huberman [38] summarized qualitative data analysis as a means to dissect meaning from the text while keeping the relations between the parts intact. Creswell [35] provides the foundation steps of qualitative data analysis, regardless of the type of methodology employed. We utilized Nvivo to do manual coding following the Creswell [35] guidelines using the following interactive steps for data analysis.

- Anonymizing and cleaning transcripts as raw data for analysis;
- Echo reading to get a general sense of the data;
- Coding data based on themes;
- Contextualizing and finding linkages between the themes;
- Interpretation of data.

4. Findings

The analysis of the text data from the interviews reveals that utilities have a well-defined scope and activities regarding the reliability of the power system, metrics to measure the reliability, and a systemized process of reporting power outages to federal authorities. However, the understanding of resilience goes beyond the scope of reliability, tracking, and reporting power outages. Resilience also encompasses community resilience and disaster resilience in the aftermath of extreme weather events. Five themes emerged based on the data - the cause of outages in power systems, the process of system maintenance, understanding of resilience, the cooperation among utilities, and regulations on resilience. The most important finding was the gap in understanding resilience as something that goes beyond grid reliability (Table 1).

4.1 Causes of outage

All interviewees identified weather-related outages as the most common in power systems. The participants classified them as significant disturbances, including big storms hitting the power system or smaller ones, such as when a bird accidentally blows out a transformer or local winds leading to a tree falling and damaging a particular distribution system line. The utilities working in the distribution system highlighted more frequent impacts on their grid and services when compared with transmission utilities. Utilities with relatively new infrastructure have the advantage of having a higher tolerance to weather-related events due to new equipment and no legacy challenges. Falling trees or vegetation are the most common reasons outlined for electricity outages. One utility outlined that "over 70% plus of all of our outages are either tree or weather-related, and they're intertwined because trees fall down a lot more during bad weather." The type of weather-related outage varies depending on the utility territory, with the most common ones identified as a hurricane, extreme wind events, earthquakes, floods, and ice storms. It is important to note that these events were not classified as mutually exclusive and can happen simultaneously. In general, utilities use approximately 30 different cause codes to categorize the reason for an outage. However, these cause codes are not uniform and can vary in terms of the nomenclature used across utilities, as the regulatory authorities do not mandate these codes at the federal or state level.

In the case of minor outages, utilities do not maintain a clear demarcation of understanding if a tree-related outage is caused by weather or by humans. For instance, as explained by one respondent, "An amateur lumberjack dropped a tree into the easement of their property and happened to dent a nearby transmission line." Most participants agreed that when a significant event impacts the system, it is generally an extreme weather-related outage. Some third-party interference, such as vehicle accidents, were relatively common; however, these occur at a relatively small scale.

Table 1. Summary of findings

Issues	Summary of theme	Scale of the issue	Relevance to resilience
Causes of Outage	Extreme weather events, followed by small local incidents, and lastly human-caused events	Distribution systems are more severely impacted compared to transmission systems. Utilities with new infrastructure can withstand impacts better than older utilities with legacy issues.	While outages and restoration is part of system resilience, restoration practices are not uniform across utilities and resilience to extreme weather events is not part of planning at either transmission or distribution scale.
System Maintenance	Most utilities conduct full system maintenance every 10 - 12 years, but there is no standard regulation nor any oversight to govern system maintenance.	Age of the system and its geographical spread determine the cost and frequency of maintenance. Distribution utilities depend on human inspection while transmission utilities have automated the process.	The lack of standard regulations reflects how utilities conduct maintenance, which is based on an informal understanding of best practices. A resilience-based regulation could involve not only maintenance but also impacts on communities.
Resilience vs Reliability	Utility managers understand resilience from a reliability perspective. While there are standard metrics to measure reliability of a system, resilience is a new concept that has not been defined yet.	Reliability is measured through SAIDI and SAIFI indicators that a utility submits to the EIA. The data is available through NERC in regions throughout the entire US. Resilience is not measured or reported by the utilities either at the transmission or distribution level.	Resilience measurement is absent. There is no metric to understand the scale of impact an outage has on consumers. The absence of indicators is a result of no agreement amongst utilities regarding the scope of resilience beyond reliability.
Cooperation among Utilities	Cooperation is based on informal agreement among neighboring distribution utilities to provide man hours prior to and post-disaster events.	Municipal utilities depend on Investor Owned Utilities (IOU) for restart of substation after outage events. There are organizational barriers that prevent formal cooperation agreements among IOUs and municipal utilities regarding the scope of maintenance at distribution level.	Cooperation is a factor of the extent of the damage, the geographical coverage of each utility, and dependence on IOU. However, with lack of formal agreements and/or rules, restoration (reliability), and resilience is open to interpretation across utilities.
Regulations	There are reliability standards at the transmission and distribution levels. However, there are no strict guidelines for resilience, particularly in the aftermath of an outage.	The absence of standardized rules and regulations is felt the most at the transmission and distribution scale. This is a top-down issue where the absence of standardization from the federal level flows down in the form of an informal understanding of what is considered essential services by utilities independently.	This is the most critical issue which influences how the transmission and distribution companies invest on resilience. Technical parameters aside, resilience is also the impact of power outage on utility services (electricity, water, gas, water, wastewater, and steam) that define community lives [39].

4.2 System maintenance

System age and the utility's size in terms of its geographical spread significantly impact how it is maintained. A smaller, newly established utility has a more robust system than an old one with significant stranded assets, particularly when another firm acquires the old system following the restructuring of the electricity sector of the US in various states. One participant outlined “the legacy costs create a significant challenge to maintaining system reliability and resiliency.” This statement highlights the synonymous use of reliability and resilience in practice. At the distribution system, a lot of maintenance and restoration work still relies on human inspection, and technology use is largely restricted to outage management systems integrated with Supervisory Control and Data Acquisition (SCADA) systems. Using SCADA depends on the utility budget and territorial spread, which is common for transmission utilities and not so common amongst small distribution utilities. Some utilities are bringing in new systems, particularly for vegetation management, to enhance the system's resilience from minor storms and weather events. However, significant penetration of such maintenance systems is still needed. Software for monitoring and inspection is more common at the transmission level, which can be attributed to the availability of more resources with the transmission companies. The average maintenance cycle for distribution companies is 12-14 years, which means one-twelfth to one-fourteenth of the system is replaced yearly in the utility geographical territory. Different utilities have varying standards for the maintenance of their system, even though most of them are based on the best practices from the industry. Each utility is free to maintain its system the way it deems fit. Hence, one utility can have a pole cycle of 12 years and others of 10 years; the same is true for other parts of the system. As one utility representative outlined, "We are in the service industry, and we have to satisfy our customers, and we choose to do it in a way which we deem best for consumers." Hence, there is no regulatory standard for the operation of utility services. The findings highlight the need for the implementation of regulations on the use of advanced technologies and systems at the distribution level for effective maintenance and restoration work. While SCADA systems are commonly used in transmission utilities, their implementation in distribution utilities is often limited due to budget constraints and the geographical spread of the distribution network. The maintenance cycle for distribution companies, which typically ranges from 10 to 14 years, further emphasizes the need for efficient monitoring and inspection systems to ensure the reliability and resilience of the distribution system. The type of technology notwithstanding, the findings point to the lack of and the need for policies at the federal level on use of technologies that can significantly improve the maintenance and restoration processes, enhance system resilience, and enable more efficient asset management.

4.3 Resilience vs reliability

Across interviews, there was consensus that resiliency is a new buzzword in the electrical utility industry. However, there is yet to be a clear and standard definition and description of the term. Resiliency was often described as synonymous with reliability; however, during the interview, three interviewees outlined that they are used synonymously but are different. There was also an expressed need to define resiliency and specify how the term should be used in the utility sector. One participant mentioned, “there are many metrics for reliability that have long existed and are well understood; there are no known metrics for resilience today.” Interviewees substantiated the claim that reliability is often associated with the SAIDI and SAIFI indicators. Furthermore, the integrated resource planners within the utility outlined that they do not use resiliency as a term for future energy systems planning and that they need quantifiable metrics for resiliency before it can be incorporated into planning and practice.

Another participant defined resilience as "reliability informs the resiliency of a power system," suggesting that reliability is a prerequisite for resilience rather than the two being synonymous. Participants further clarified that reliability refers to the ability to keep the majority of the lights on most of the time, while resilience is the capacity to respond to and recover from high-impact events. One interviewee mentioned that the definition of resilience should also account for the resilience of the relationship between the utility and its consumers and how waning trust between customers and the utility can be restored. The common theme regarding power system resilience is the need to develop temporal indicators that can measure the system's bearing capacity for different levels of impact, its level of adaptability, and the amount of transformation required for the system to remain reliable.

Findings suggest the importance of distinguishing reliability and resilience in the context of power systems. Critical to this distinction is the temporal aspect of resilience, wherein indicators for pre-, during, and post-event impacts are needed to understand the impact on communities. Enhancing community resilience is tied to the temporal aspect - trust and communication between utilities and consumers before, during, and after extreme events. Another aspect of community resilience is understanding how energy services are differentiated among customers; people living in older housing are more vulnerable to disruptions to heating and cooling services, as are residents with very young or very old household members. Medically vulnerable consumers who need electric power to maintain access to necessary medical equipment face different vulnerabilities than those who are healthy. Based on the interviews, this aspect of community resilience, recognition of energy services access, and its link to social vulnerabilities is currently missing from considerations of reliability and resilience in the power sector.

4.4 Cooperation among utilities

Interviewees outlined that utilities have signed and, more commonly, unsigned agreed upon understandings for helping neighboring electrical utilities, particularly in the distribution system. In case of an anticipated disaster, helping other utilities by sending the crew at standard labor rates is practiced. In case of more significant disasters in terms of geographical scale and scope, the crew also arrives from further away utilities, and that time lag to accessing the necessary labor for restoration work to begin cannot currently be classified under the resiliency of the system as it is not based on any of the reliability indicators within the power sector. During high-impact events, cooperation among utilities can also be hindered by organizational barriers and arrangements.

Interviewees mentioned that cooperation is a key element of recovery because, in case of an event requiring additional workforce and equipment for pre-staging or post-event work, utilities cooperate in providing the services. One respondent stated, "In my mind, the biggest thing we need to do is better coordinate for preparing for mutual aid activities," which, in most cases, is based on informal understandings as identified in this statement, "It's just an understanding basis, say hey, you know, come on over and help us out; we'll send you a bill and help you during your situation."

The structure and geography of a particular utility system can significantly influence its response to outages. As explained by several participants, when an outage occurs in a small municipal utility proximate to the service territory of an investor-owned utility (IOU), or vice versa (although the former scenario is more common), even after the municipal utility restores its distribution system, they may still have to wait for the IOU to restore or reboot the substation, leading to a delay in power restoration. The municipal utility typically pays kneeling charges to the IOU for maintaining the substation. This situation arises when an IOU has a significant territory and does not, or to some extent, cannot maintain a contractual relationship authorizing the municipal utility to work on the substation. While the municipal utility can repair distribution lines, the substation may fall under the IOU's jurisdiction, and interviews discussed this exact situation as one highlighting the need for cooperation between utilities.

4.5 Regulations for resilience

One crucial aspect of the restoration process is the prioritization of essential services and critical infrastructure. These terms refer to facilities and services that are vital for the functioning of a community, such as hospitals, emergency services, water treatment plants, and communication networks. Ensuring the continuous operation or prompt restoration of these services is crucial for public safety and minimizing the impact of outages. While utilities follow reliability standards at the transmission and distribution levels, there are no strict guidelines dictating restoration processes. Instead, utilities rely on their own best practices, which leads to inconsistencies in priorities and procedures.

There are 16 Critical Infrastructure (CI) sectors according to the National Infrastructure Protection Plan (NIPP) [40]. Within those CIs are “lifeline functions,” which refers to a sector that provides indispensable services that enable the continuous operation of critical business and government functions and that would risk human health and safety or national and economic security if compromised or not promptly restored. These lifeline functions include communications, energy, transportation, and water. However, the participants highlighted that the definition of what constitutes an essential service or critical infrastructure is not uniformly defined by external agencies; instead, each utility determines its own criteria, particularly at the distribution level. This lack of standardization can lead to discrepancies across different utility service areas, where certain facilities, such as nursing homes or schools, may be prioritized in one area but not in another.

5. Discussion

The future of energy resilience from a utility perspective is increasingly intertwined with reliability concerns, particularly in light of emerging technologies, changing energy consumption patterns and a changing global climate. Utilities are grappling with the challenge of adapting their infrastructure to accommodate the growth of electric vehicles (EVs) and the increasing electrification of various services. As one participant noted, "One of the things we're looking at is upgrading our distribution system to meet the demand for electric vehicles and other things; we are going to have to have something more robust if everybody is plugging in a car." This sentiment reflects a broader concern among utilities, especially municipal entities, as they strive to enhance system capacity and robustness to meet evolving electricity demands.

The increasing reliance on electricity for essential services such as heating, cooling, lighting, communication, and food storage amplifies the potential impact of even minor outages. As stated earlier, the NIPP (2013) has defined 16 Critical Infrastructure (CI) sectors, and within those CIs, it has defined “lifeline functions,” which refers to a sector that provides indispensable services that enable the continuous operation of critical business and government functions, and that would risk human health and safety or national and economic security if compromised or not promptly restored. To address the challenge of ensuring lifeline functions, utilities are considering various technical solutions to enhance both reliability and resilience. These include investments in storm hardening measures, such as reinforcing poles and wires and transitioning from overhead to underground distribution lines. Additionally, utilities are exploring the implementation of Distribution Automation and remote Supervisory Control and Data Acquisition (SCADA) systems to improve system monitoring and control capabilities. However, different utilities prioritize different aspects of resilience, and there is no specification on what constitutes essential services in a utility territory. The implementation of these identified resilience-enhancing measures presents a significant economic challenge. The costs associated with modernizing transmission and distribution systems are substantial and would likely be passed on to customers. This economic burden creates a tension between the need for infrastructure upgrades and the imperative to maintain affordable electricity rates. Utilities face the complex task of justifying these investments to both regulators and customers, often in unfavorable regulatory and public opinion environments.

The findings suggest the need for further research on defining the scope and measurement of resilience at the transmission and distribution levels. This research can be expanded upon by including the perspectives of the impacted communities and resilience impacts after power outage events. The lack of consideration of the impact of power outages on essential services and challenges faced by vulnerable communities during outages requires broadening of our understanding of resilience and establishing standard metrics for measuring resilience impacts of outages. Participants are aware that climate-induced disasters will increase in the future, leading to a higher probability of system outages. This finding confirms current research on how increasing climate disaster events would risk power system reliability [41, 42]. Extreme weather events are now a significant cause of power system failure beyond the contingency of N-1-1 for the events that are financially unfeasible to plan for as they are once-in-a-lifetime events. Hence, the participants agreed that they need indicators and a framework for applying resilience in the utility sector. Currently, resilience is being used synonymously with reliability without any specific framework on how and on whom the benefits and the costs associated with adapting to resilience are to be distributed. The lack of focus on energy service vulnerabilities also leads to a lack of not understanding of how consumers energy service needs are differentially impacted. As power systems are only a means to serve people's energy needs, there is a need to look at people's energy service needs while considering the power system's resilience [43]. The increasing reliance on electricity for essential services such as heating, cooling, lighting, communication, and food storage amplifies the potential impact of even minor outages. This heightened vulnerability underscores the need for improved system resilience [42]. The absence of standardization on what constitutes critical or essential services across utilities is another cause of concern. Communities' specific needs and vulnerabilities can vary based on their geographic location, socioeconomic characteristics, and existing infrastructure [44]. Although the importance of different categories of services at times might not vary across groups, the communities' specific needs and vulnerabilities still vary since these needs could depend on housing characteristics (e.g., house insulation level), specific comfort requirements across individuals, and health needs of occupants [45]. Research also indicates that utilities can prioritize different services based on their customer base, revenue considerations, and organizational priorities [46]. This understanding reflects a broader concern among utilities, especially municipal entities, as they strive to enhance system capacity and robustness to meet evolving electricity demands [47]. A key finding that has been prominent in the field of disaster resilience [48], is the importance of stakeholder cooperation. As highlighted by most interviewees, utilities support each other in case of emergencies and system failure. However, this is mainly done through mutual understanding and rarely with written agreements. Utilities in most of the US have eminent domain and now they are trying to compete with each other for customers [49]. Therefore, in cases of competing interests and nested jurisdictions, cooperation during system failures requires a more nuanced understanding.

Lack of agreement among transmission and distribution utilities in the US regarding resilience indicators is further evidenced by other studies. Bie et al. [50] note that different utilities prioritize different aspects of resilience based on their region-specific vulnerabilities and experiences with past disruptions. With electricity being a central element in providing services for every aspect of human life, it is important to articulate how resilience is defined for people and the criteria for restoration and recovery of energy services. This disparity in focus can lead to inconsistent approaches to measuring and improving resilience across the power sector. There is a need to develop a common understanding of the meaning of resilience in the utility sector and develop the means of measuring it and including resilience in integrated resource planning. The practitioners interviewed in the electrical utility sector did not identify a single definition of energy resilience. As often done in engineering studies, participants articulated energy resiliency as synonymous with reliability. There is a clear agreement that reliability indicators are clearly defined and measurable through data submitted to EIA and other reporting requirements of utilities regarding power outages to NERC. However, the scope and definition of resilience are vaguely understood and misplaced with reliability in terms of standard metrics. Resilience is temporal in nature and includes aspects of recovering after a disaster. This element is not covered in any reliability indicator on how long the distribution system should deter the impact of an event and how quickly it has to recover from the impact and be prepared for the subsequent failure. Furthermore, differential impacts on different segments of the population are also a key factor missing from practitioners' understanding of resilience. Umunnakwe et al. [51] have proposed a categorization scheme for quantitative power system resilience metrics. The categorization scheme in the study by Umunnakwe et al. [51] reflects the multifaceted nature of resilience, encompassing aspects such as robustness, resourcefulness, rapid recovery, and adaptability. However, the development of universally accepted quantitative indicators remains challenging due to lack of agreement among utilities on what constitutes resilience.

6. Conclusion

Through the study, we explored how electrical utilities think of, and practice resilience in the context of power systems, which are increasingly affected by the increasing impacts of climate change. Our analysis of the interviews provides valuable insights into how electrical utilities conceptualize and implement resilience in the face of increasing climate change impacts. This case study on resilience is novel because academic literature has not looked into understanding resilience from an energy service perspective and the ways in which practitioners in the electrical utility sector understand and use the term. It highlights the need for a more contextualized understanding of resilience that goes beyond grid stability, emphasizing the importance of clearly defined critical services and vulnerable populations. However, this study does not represent the understanding of the entire utility sector in the US. Hence, no attempt is made to generalize the results of this study using a small sample of interviews conducted. The scope of the study was limited as the approach was to dig deep into understanding the perspective of a wide range of utilities from different geographical regions in the US. The findings are still relevant given the methodology of studying resilience and understanding a particular sector's perspectives. As electricity becomes increasingly central to all aspects of human life and the energy landscape evolves with electrification and retail choice, a nuanced approach to power system resilience that considers both technical and social dimensions is crucial for future planning and policy development.

Ethical issue

The authors are aware of and comply with best practices in publication ethics, specifically concerning authorship (avoidance of guest authorship), dual submission, manipulation of figures, competing interests, and compliance with policies on research ethics. The authors adhere to publication requirements that the submitted work is original and has not been published elsewhere in any language.

Data availability statement

The manuscript contains all the data. However, more data will be available upon request from the corresponding author.

Conflict of interest

The authors declare no potential conflict of interest.

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